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Life cycle environmental impacts of the apparel industry in Sri Lanka: Analysis of the energy sources

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ABSTRACT

The apparel industry is responsible for 10% of the world's carbon emissions, and is considered as the second highest industrial polluter after the oil industry. In Sri Lanka, the apparel sector is the key foreign revenue earner, and developing a sustainable apparel industry will provide a competitive and strategic advantage to the Sri Lankan apparel products in the global market. However, limited data availability and a lack of studies carried out to quantify environmental impacts and propose mitigation strategies have detrimentally affected the growth of the Sri Lankan apparel industry. This study proposes a framework to quantify the environmental impacts due to energy use in garment production in the Sri Lankan apparel industry. Initially, the impacts were quantified using life cycle assessment with a gate-to-gate approach, based on the specific energy use and energy sources being used in the major production and transportation phases in a garment's life cycle. A case study was then conducted based on the data from an apparel production facility located in Sri Lanka. The life cycle impacts of energy use of the selected process phases were compared to identify the most critical processes in terms of the environmental footprint. Finally, the study was extended to investigate the effects of using different alternative energy supply scenarios. The life cycle impact assessment was conducted using the ReCiPe (Ver 1.11) Midpoint method in SimaPro. The findings revealed that the garment production phase carries the highest life cycle impacts among the studied process phases from fabric manufacture to distribution to the end market. Scenario analysis showed that the use of solar photovoltaics and biomass to supply the required electricity and thermal energy for apparel manufacturing can reduce climate change, ozone depletion, and terrestrial acidification by 90–95%. This information can be used by decision makers to plan for sustainability and growth of the apparel industry.

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1. Introduction

Energy use and related environmental impacts are a source of major concern in the present-day world (Agrawal et al., 2015). The International Energy Agency (IEA) reports that two thirds of the total global greenhouse gas (GHG) emissions (and 80% of the CO_2 emissions) are accounted for by the energy sector (International Energy Agency, 2015). The GHGs and other toxic emissions associated with energy consumption have been linked to anthropogenic climate change, resulting in adverse environmental effects such as global warming (Ellabban et al., 2014; Environment and Climate Change Canada, 2015). The attention shed on energy use in various industries has increased with the awareness about fossil fuel depletion, particularly with the rise of industrialisation and the corresponding growth in energy use across the world (Bilgen et al., 2004). With the above-mentioned concerns on energy use and its environmental effects, climate action goals have been set in motion. At the Paris Climate Agreement (COP21) held in 2015, 195 countries agreed to limit and reduce emissions in order to battle the threat of climate change (European Commission, 2016).

The global manufacturing industry in its various forms results in significant energy use and emissions (Kucukvar et al., 2016). The industrial sector consumes around 54% of the world's total energy delivery. In 2012, the manufacturing sector used 66% of the

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Nomenclature

Acronyms

FG	Finished good
GDP	Gross domestic product
GHG	Greenhouse gas
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
RM	Raw materials
RE	Renewable energy
SL	Sri Lanka
USD	United States dollars

Units

MJ/tkm	Mega Joules per tonne-kilo metre
kWh/kg	kilowatt hours per kilogram produced
kJ/kg	Kilo Joules per kilogram produced
kg 1,4 DB eq	kilogrammes of 1,4 dichlorobenzene equivalent
kg CFC-11eq	Kilogrammes of Trichlorofluoromethane equivalent
kg CO_2 eq	Kilogrammes of Carbon Dioxide equivalent
kg N eq	Kilogrammes of Nitrogen equivalent
kg NMVOC	kilogrammes of Non-Methane Volatile Organic Compounds
kg P eq	Kilogrammes of Phosphorus equivalent
kg SO_2 eq	Kilogrammes of Sulphur Dioxide equivalent

consumed energy, thus accounting for 35.6% of the overall global energy consumption (U.S. Energy Information Administration, 2016). Furthermore, the global industrial energy consumption is expected to grow at an annual rate of 1.2% (U.S. Energy Information Administration, 2016). Therefore, focus on energy consumption and related emissions with respect to different industry sectors is crucial in order to propose action**s** for mitigating adverse environmental and health impacts.

The apparel industry in particular is a substantial energy consumer, and results in environmental and health related risks (Claudio, 2007). It is reported that the apparel industry is responsible for 10% of the world's carbon emissions, making it the second highest industrial polluter after the oil industry (Conca, 2015). However, pollution due to apparel industry sector has not been discussed sufficiently in the literature, probably due to being in the shadow of the oil and gas industry in terms of environmental impacts. Thus, it is important to conduct in-depth studies on environmental and health impacts of the apparel manufacturing industry with a view to formulate impact mitigation actions. In addition to providing solutions to the environmental issues, energy sustainability approach can also help in easing the economic burden of manufacturing (Agrawal et al., 2015).

1.1. Life cycle assessment (LCA) in industrial applications

Life cycle assessment (LCA) provides a holistic approach in evaluating the environmental impacts of a production process comprehensively, thus enabling well-informed decision making (Kucukvar et al., 2016; Varun et al., 2009). It is also an internationally standardised environmental assessment approach, defined through ISO 14040 series of standards (Kloepffer, 2008). Therefore, it can be used as an approach to quantify the environmental impacts across all the phases in the life cycle of a product or a process. In order to quantify the life cycle impacts pertaining to a particular industrial application in a given context, local data and assessments thus become essential (Turconi et al., 2011). Therefore, LCA can be considered as a data intensive process, and lack of data will lead to uncertainties in the assessment (Rana et al., 2015), resulting in limited applicability of the method. This poses challenges, particularly in the context of developing countries where stringent monitoring measures are not applied and hence the availability of required data is limited.

In developing a sustainable apparel industry in terms of energy use as well as environmental and economic impacts, it is necessary to study the energy use of the garment production process throughout its life cycle. The life cycle of a garment can be separated into several phases such as production of fiber, yarn, fabric, and garments, consumer use, and eventual disposal at the end of life (Rana et al., 2015). The life cycle environmental impacts of the textile and apparel industry include resource depletion, water use and toxic by-product generation in addition to GHG emissions (Claudio, 2007). These adverse impacts are caused by processes that take place during all the stages of a garment's life cycle, from sourcing of raw materials for fibre production and the use of energy in the production processes, to the end-of-life disposal (Kozlowski et al., 2012). The true costs and impacts of the apparel industry can therefore be only identified through adoption of life cycle thinking.

The life cycle impacts associated with energy use in manufacturing is a special area of concern due to the high energy intensity of the sector. In order to obtain a complete picture of the energy use and the associated environmental performance of a product or a process, its entire life cycle needs to be considered in the assessment (Cheah et al., 2013). At present, much of the energy performance assessments carried out in the industrial sector tend to be focused on the direct energy use and its resulting emissions in the production process, hence neglecting the impacts and embodied energy pertaining to the other phases of the life cycle such as material production, transportation and waste disposal (Cheah et al., 2013; Kozlowski et al., 2012). Further, while the direct carbon emissions due to energy use are being considered in environmental impact assessments related to different energy sources, the life cycle impacts of energy generation (from infrastructure development to end-of-life) are generally neglected (Hertwich et al., 2015). These limitations not only result in underestimation of the actual impacts of a production process, but also prevents the identification of potential areas of improvement. Employing a life cycle thinking approach will aid in identifying the most critical areas of concern and potential improvement strategies related to energy use in the apparel industry, as well as in making the most informed decisions for a sustainable industry (Laurenti et al., 2016).

1.2. Apparel industry in Sri Lanka

In Sri Lanka (SL), the apparel sector is the largest foreign revenue earner and employment generator among the industries (Board of Investment of Sri Lanka, 2016). The sector generates around 4.4 billion USD in export income each year, and SL is a leading apparel producer in the South Asian region, outperforming the competitors in terms of quality, reliability, lead time, and social accountability (The World Bank, 2016). Accounting for around 49% of the country's total export earnings in 2016, this is a vital industry for the country's economy (Central Bank of Sri Lanka, 2016). The overall growth in the Sri Lankan wearing apparel subsector is 16% as per 2015 statistics (Central Bank of Sri Lanka, 2015).

SL apparel production caters to a number of reputed international brands such as Victoria's Secret, Nike, Tommy Hilfiger and Ralph Lauren (Board of Investment of Sri Lanka, 2016; Cordón et al.,

2012). It has been identified that the apparel sector in Sri Lanka should identify niche markets and improve brand identity in addition to enhancing price competitiveness in order to maintain its performance in the global markets (Central Bank of Sri Lanka, 2015). The energy demand of the sector is fulfilled through a mix of sources that includes grid electricity, diesel, furnace oil, kerosene, LPG and biomass (Sri Lanka Sustainable Energy Authority, 2016). There is growing notice, especially among the large-scale apparel producers of Sri Lanka, in energy efficient and environmentally sustainable production practices (Sri Lanka Export Development Board, 2016). However, there is only limited data currently available on the environmental impacts in Sri Lanka due to the lack of monitoring and regulatory procedures (Zubair, 2001). This issue needs to be addressed in developing an environmentally sustainable industrial sector. At the global level, there is increasing interest in sustainable and "eco-friendly" products (Llorach-Massana et al., 2015). As consumers become more aware of the environmental burdens of the goods they use, the demand has risen for higher environmental accountability in the production sector (Kozlowski et al., 2012). Therefore, the Sri Lankan apparel industry can benefit from the integration of the environmental sustainability concept with life cycle thinking in its production process. Moreover, this approach can translate to economic benefits to the apparel industry through direct and indirect cost savings related to energy and resources (European Commission, 2010). It has also been found that the consumers are willing to pay premium prices to obtain "green" products (Drozdenko et al., 2011). Thus, environmentally conscious production and green labelling may further provide a competitive advantage for SL apparel in the international market (Gunathilaka and Gunewardena, 2014).

The aim of this study therefore was to investigate the effects of energy use in the Sri Lankan apparel sector and propose a framework for assessing the resulting life cycle environmental impacts of energy use. Under this, the specific objectives were to explore the energy use in the main production and transportation phases of a garment's life cycle undertaken within Sri Lanka, to quantify the environmental impacts due to energy use in the identified phases, to identify the most critical processes in terms of the environmental footprint, and to investigate the effects of different alternative energy supply scenarios. The study highlights the limitations and challenges faced by the Sri Lankan apparel industry in integrating sustainable production concepts based on life cycle thinking, and discusses the need for filling in the gaps in available information. It is expected that the study will address the gaps in life cycle energy use analysis and environmental performance data in the apparel sector in SL in particular and developing countries in general, and help decision makers to plan for a more sustainable industry.

2. Methodology

A literature survey was initially conducted to explore the major phases related to production and transportation of garments. This led to the development of a methodology to assess the life cycle environmental impacts associated with the energy consumption. Then, a case study was conducted based on the data from an apparel production facility located in SL where a life cycle assessment based on the specific energy use and energy sources was carried out for a selected standard garment manufactured in the facility. Finally, an impact assessment was carried out for the possible variations in the environmental performance of the garment production process with respect to different energy supply scenarios. The scenario of undertaking fabric manufacture in Sri Lanka was also investigated for the same facility. The findings of the study were used in identifying the intensity of environmental impacts of key process phases, and to investigate the potential of mitigating negative environmental effects (performance enhancement) under alternative energy scenarios. This information was used in providing recommendations for the SL apparel sector. The details of the study are described below in the subsequent sections.

2.1. Life cycle assessment methodology

Four phases have been defined for a LCA under ISO 14040 (Ristimäki et al., 2013). The LCA for the current study was conducted according to these four phases. First, the goal and the scope need to be defined. The goal of an LCA is defined through the intended application and use of results, target audience, and the reasons for conducting the study (The International Standards Organisation, 2006). The scope of an LCA includes the product system, which studies the system boundary, functional unit, allocation procedures, selection of impact categories, and assumptions (The International Standards Organisation, 2006). There can be different definitions of system boundaries, such as cradle-to-grave (raw material extraction to disposal at end-of-life), gate-to-gate (between intermediate process phases), and cradle-to-gate (raw material extraction to intermediate process) (The International Standards Organisation, 2006; Van Der Velden et al., 2014). In the second phase, which is life cycle inventory analysis (LCI), data collection and quantification is carried out on the inputs and outputs of the product system (The International Standards Organisation, 2006). Here, the resources, energy, and waste together with transportation activities from and to each of the process stages need to be recorded for every stage of the process. This is the stage where the data specific to the case study area need to be brought in. In the third phase, The life cycle inventory data is used to evaluate the environmental impacts of the product system (The International Standards Organisation, 2006). This is known as the life cycle impact assessment. Different impact categories are used in representing the life cycle environmental impacts, based on the goal and scope (The International Standards Organisation, 2006). The fourth and final phase of the methodology is interpretation. The results delivered in the interpretation of the LCA findings should align with the goal and scope defined. These may be in the form of conclusions and recommendations, targeted at the decision makers and other stakeholders (The International Standards Organisation, 2006).

2.2. Case study

The production of a 100% cotton blouse in a SL apparel production factory was selected as the focus of the case study. The cutting of the fabric and the assembly of the garment through sewing were carried out in SL at the selected apparel production facility. The raw materials for the garment are sourced from foreign suppliers located in India. The end market of the finished product is in the USA. The product description for the case study is as follows.

Product description:

End product: Short-sleeve-blouse

Standard Allowed Minutes[1]: 29.82

Mass: 0.146 kg

Fabric:

Warp (yarn size in English count): 60Ne; Weft (yarn size in English count): 60Ne

Number of ends per inch: 104; Number of picks per inch: 88

Weight: 75gsm

Weave: 1/1, Plain

[1] The total number of minutes allowed in completing a process or operation in a standard environment for a standard worker.

Dyeing technique: Solid piece dyeing
Finished width: 58”

The bill of materials for the finished product is given in Table 1. It shows the components needed to produce a single blouse.

Table 2 lists the spatial locations of each sub-process in the garment's life cycle. The data was acquired based on the location of the process. It was identified that the transportation from port to factory and factory to port is done entirely by means of road transportation, while transportation between countries is conducted via ships. The sourcing of fabrics and distribution of the finished goods to consumer markets is done via freight transport.

2.3. Life cycle assessment

The system boundary needs to be selected based on the most direct concerns for the apparel industry, to indicate the scope of unit processes taken into account in the analysis (The International Standards Organisation, 2006). Out of the scope definition approaches described in LCA (The International Standards Organisation, 2006), the “gate-to-gate” approach was selected for the study (Laurenti et al., 2016). The focus of the LCA was on the manufacturing phase of fabrics and garments, as this encompasses the area of concern with regard to energy consumption in the apparel industry. While the total life cycle energy use of a garment includes all the processes from extraction of raw materials (for fibre production) to eventual disposal of garments (Van Der Velden et al., 2014), the selected processes within the LCA system boundary were identified as the most direct concern for the apparel industry. As such, the impact assessment was conducted only for the fabric and garment production, and distribution phases of the SL apparel industry. As the target audience of the study is the Sri Lankan apparel industry, the analysis was focused only on the process phases undertaken in SL.

With these insights, the system boundary of the LCA for the current study was defined as shown in Fig. 1. The components were screened for the most critical items based on the amount used in a single product unit. Therefore, cotton fabric (main fabric and interlining), and threads were selected as the components of concern. The blouse was selected as the overall functional unit of the assessment, while different functional units were considered as appropriate when defining the LCI under the various sub-processes. Packing materials, buttons, thread and labels were not considered in the analysis.

After defining the system boundary, the process phases currently undertaken within Sri Lanka (i.e. from fabric acquisition to the transport of finished items to port for distribution) were analysed with respect to their energy consumption. The life cycle impacts of different energy sources used in electricity and thermal energy generation were quantified through the ReCiPe Midpoint method (version 1.11) in SimaPro software with the data from the Ecoinvent 3 database. ReCiPe is a method which is harmonised in modelling principles and choices, and has both midpoint and endpoint impact categories (Hischier et al., 2010). The Midpoint indicators represent the elementary flows and other environmental exchanges characterised by the impact category (Hischier et al., 2010). ReCiPe method at its midpoint level uses 18 impact categories to illustrate the environmental impacts. The midpoint level is damage oriented, and the uncertainty associated with the results is lower (PRé, 2016). They are generally more accurate than endpoint ones (which are used to represent the “damage” or the overall impact in terms relatable to the public) (United Nations Environmental Program, 2011). Since the purpose of the study was to quantify and compare the environmental impacts of energy use under various production phases and scenarios, and not to interpret LCA results, midpoint indicators were selected as parameters of environmental performance. Similarly, the life cycle impact assessment was also conducted on the transport phases considering the different fuel types used.

The impacts were aggregated using the energy use information for each process step, and thereby allocated to the garment in the case study. The functional unit of impact assessment for transportation was taken as one tonne-kilometre (tkm), while the functional unit of energy use was taken to be 1 kW hour (kWh). The total impacts per garment were estimated based on the standard minutes allocated per each garment. The specific energy use for SL apparel production facilities, and the SL electricity mix were considered in the analysis.

2.3.1. Normalisation method for comparison of results

To compare the life cycle impacts of the different process phases and under different energy sources, the obtained impact indicator data was normalised. ISO 14044 identifies normalisation as an optional step in LCA which follows the impact characterisation phase (Benini et al., 2014). In life cycle assessment, two methods of normalisation are commonly used, namely internal and external (Norris, 2001). In internal normalisation, case-specific normalisation is conducted, where the impact values are divided by the maximum within the impact category, or by the sum of the values in the impact category (Norris, 2001; Myllyviita et al., 2012). Another method is to assume a selected alternative as a baseline, and take a “divide by baseline” approach (Benini et al., 2014). In contrast, external normalisation method requires a normalisation factor, defined based on the total impacts in an indicator category under a selected reference system, which can be per person or for a system or region during a given period (e.g. a year) (Myllyviita et al., 2012; Benini et al., 2014).

For this study, an internal normalisation process was selected, as the objective was to compare the environmental impacts between the different life cycle phases in apparel production. Internal normalisation has the advantage of not requiring any data outside of the case study (Norris, 2001). A “division by sum of impact values” was taken in the normalisation, with the normalised impact score for ith impact category being represented by the following equation (Myllyviita et al., 2012).

$$N_{ij} = \frac{IM_{ij}}{\sum_j IM_{ij}}$$

Where;

IM_{ij} = Indicator value of the ith impact category for the jth process phase
N_{ij} = Normalised value for the indicator
j = number of compared items (process phases)

A “divide by baseline” approach was employed in comparing

Table 1
Bill of materials for the selected product.

Component	Unit	Consumption
Fabric	m	1.32
Button	Pcs	10
Thread [120ticket[a]]	m	320
Thread [220ticket]	m	140
Interlining	m	0.28
Care label	Pcs	1
Size label	Pcs	1
Main label	Pcs	1

[a] Ticket = Nm × 3 Where Nm is the metric count of the thread.

Table 2
Spatial locations of the processes.

Processes	Location	Shipping distance
Raw material production (for fibre, yarn, and fabric)	India	–
Manufacturing of end products	Sri Lanka	–
Transportation: port-to-factory (RM) and factory-to-port (FG)	Sri Lanka	140 km
Transportation: by ship (RM and FG) [a]	India - Sri Lanka Sri Lanka – USA	~1650 km ~20720 km
Product use	USA	

[a] Distances are provided based on average shipping route distances to the selected ports in India and USA.

different alternative energy scenarios in apparel production. In this, k represents the number of different energy scenarios considered, and IM_{ik} is the indicator value of the ith impact category for the kth energy scenario. IM_{ib} refers to the impact value of the baseline case, which is the "business-as-usual" scenario.

$$N_{ik} = \frac{IM_{ik}}{IM_{ib}}$$

In comparing the energy scenarios for apparel production, the aggregated life cycle impacts of fabric production and garment production phases were considered, as these are the process phases affected by a substitution in energy sources.

2.4. Data for the analysis

On top of the garment specific information (i.e. product profile, bill of material and special location of processes), the data on energy use and their sources was needed to develop the life cycle inventory for the analysis. Furthermore, a plausible set of alternative energy sources for the comparison of supply scenarios were considered for the analysis.

2.4.1. Energy use and sources

According to the context of the case study, the energy use within the LCA boundary was chiefly accounted for by electric and thermal energy in the manufacturing facilities, and fuel for transportation. The energy sources used in garment production were aggregated for a standard clock hour. Evidence from previous studies suggests that the energy intensity of road freight transportation in India falls in the range of 1.2–1.8 MJ/tkm (Tiwari and Gulati, 2013; Zhou et al., 2007). Accordingly, the energy intensity of road transport for factory-to-port and port-to-factory scenarios was assumed as 1.8 MJ/tkm under pessimistic conditions. The energy intensity of sea transport via container ships was averaged at 0.2 MJ/tkm based on the literature (Tiwari and Gulati, 2013; Michaelowa and Krause, 2000; Kristensen, 2002). A study in 2010 sets the specific energy consumption in producing 1 kg of woven fabric at 5.06 kWh of electric energy and 9.85 kJ of thermal energy (Koc and Çinçik, 2010). Other literature sets a range of possible values from 1.35 to 10.63 kWh/kg in specific electric energy consumption for fabric production, which is in line with the above results (Van Der Velden et al., 2014). The thermal energy is mainly supplied through coal (Koc and Çinçik, 2010). This data was assumed to be partly representative of the fabric manufacturing and distribution in South Asia. The distance from the garment manufacturing facility (located in Sri Lanka) to the port is 140 km. The average shipping distances from supply locations to the end markets were used in assessing the energy use in sea transportation (i.e. the average shipping distances), as mentioned in Table 2.

The data published by the Sri Lanka Sustainable Energy Authority on the average energy supply mix for a standard clock hour in a SL apparel manufacturing facility was used in assessing the energy use in garment production (Sri Lanka Sustainable Energy Authority, 2016). This information is given in Table 3. The energy generation information in the Sri Lankan Energy Balance published by the Sri Lanka Sustainable Energy Authority (Sri Lanka Sustainable Energy Authority, 2014) was also used to determine the grid electricity generation mix, which is detailed in Table 4.

Then, the scenario of undertaking fabric manufacture in Sri

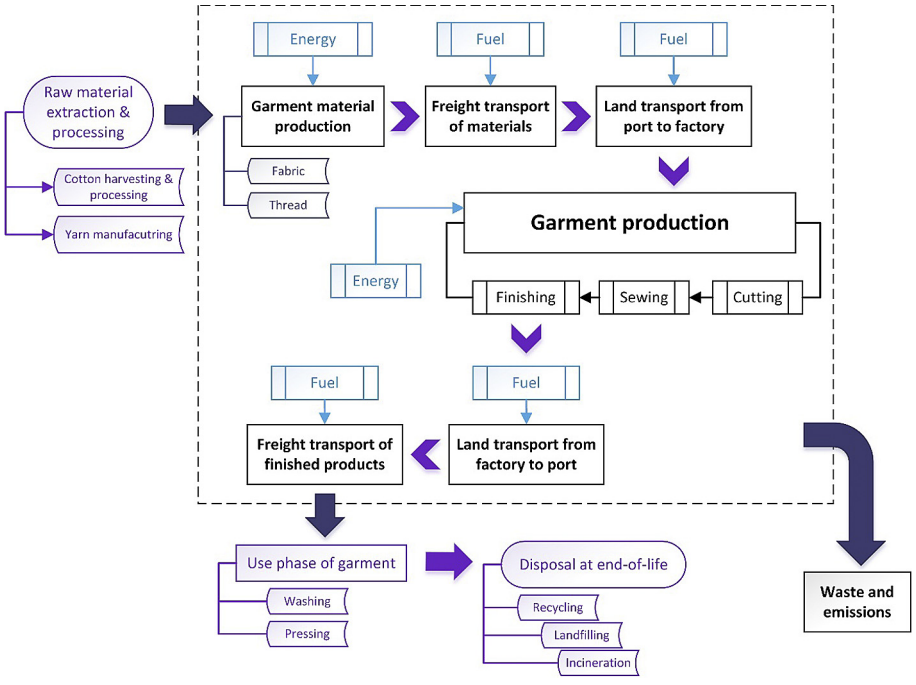


Fig. 1. LCA system boundary for the production process.

Table 3
Specific energy consumption in Sri Lankan apparel industry (Sri Lanka Sustainable Energy Authority, 2016).

Energy supply	Unit	Average consumption
Grid electricity	kWh/Clock Hour	1.31
Diesel – Electric	Litres/Clock Hour	0.008
Diesel – Thermal	Litres/Clock Hour	0.031
Biomass – Thermal	kg/Clock Hour	0.17
Furnace oil – Thermal	Litres/Clock Hour	0.096
LPG – Thermal	kg/Clock Hour	0.01
Kerosene - Thermal	Litres/Clock Hour	0.018

Table 4
Electricity generation mix for Sri Lanka.

Source		Generation (GWh)	Percentage (%)
Major hydro		3649.7	28.45
Thermal	Coal	4419.3	34.44
	Oil[a]	3525.0	27.47
Renewable	Mini-hydro	902.2	7.03
	Biomass	41.4	0.32
	Solar	1.5	0.01
	Wind	291	2.27
Total		**12,830.1**	**100**

[a] The mix of liquid fossil fuel types used in thermal power generation is fuel oil (24%), residual oil (26%), diesel (35%) and Naphtha 15%).

Lanka was investigated for the same facility. The increase in energy use and the resulting escalation of life cycle impacts were identified for this scenario.

2.4.2. Alternative energy supply scenarios

To assess the effect of replacing the conventional energy sources with sustainable alternatives, different energy supply scenarios were explored for the fabric and garment manufacture phases. Scenario based assessment has been considered in previous studies in investigating energy use and the resulting environmental impacts, and to compare different energy sources (Karunathilake et al., 2016). At present, the Sri Lankan apparel industry is moving towards non-conventional energy sources, with the major apparel producers investing in solar and biomass for their energy needs (Henricus, 2012). Installing solar PV technology in their manufacturing facilities and replacing oil-based boilers with biomass are some common initiatives across the industry (Brandix Ltd,).

Table 5 details the energy supply scenarios, which were considered in the study. The life cycle impacts of different energy sources were assessed under each scenario. The aggregated impact indicator values for fabric and garment manufacture phases were used to compare the life cycle impacts of conventional energy supply in "business-as-usual" scenario, with replacement scenarios. The first scenario represents the business-as-usual case, and the second and third scenarios consider 100% replacement of electric and thermal energy sources with solar PV and biomass respectively. In the fourth scenario, the conventional sources for electricity and thermal energy are partially (50%) replaced with solar PV and biomass. The final scenario explores the effects of completely replacing the conventional sources with solar PV and biomass.

The transportation fuel usage data indicated in Section 2.4.1 and the average shipping distances from India to SL and SL to USA were considered in the analysis. As the fabric manufacture is expected to be carried out by the same facility, the impacts due to transportation from fabric manufacturer to garment production were assumed to be negligible for the purpose of this study.

2.5. Environmental performance assessment

The previous sections detailed an environmental performance assessment methodology for the energy use in the apparel sector based on life cycle thinking. The methodology proposed for the Sri Lankan apparel industry based on the investigations is summarised in Fig. 2. The goal and scope definition was carried out to suit the needs of the target audience, i.e. Sri Lankan apparel industry and the government bodies in charge of regulating industrial practices. The energy use has been investigated in this study, under the key process phases considered in fabric and garment manufacturing. A scenario-based approach was taken in assessing the potential benefits of alternative energy scenarios for the industry.

3. Results

It is assumed that the same distribution in specific energy use described in section 2.3.2 is applicable for fabric production in SL facilities. It is also assumed that the use of thermal energy sources in fabric production to occur at the same mix as the standard energy supply in SL garment manufacturing facilities, based on the information provided by the Sri Lanka Sustainable Energy Authority. Thus, the thermal energy mix stands at diesel – 13.2%, biomass – 31.2%, furnace oil - 43.2%, LPG – 5.1%, and kerosene 7.2%. The total mass of fabric in the body of the garment can be considered as 0.146 kg as per the case study data. The life cycle impacts of garment production is shown in Table 6.

The impacts of the transportation phase are presented for the supply of material for garments (and fabrics) from India, the transport of material from port to factory, the transport of finished items from factory to port, and the distribution of finished products to the US market in Table 7. As the fabric manufacture is expected to be carried out by the same industrial facility, the impacts due to transportation from fabric manufacture to garment production were assumed to be negligible for the purpose of this study.

Table 5
Energy supply scenarios for fabric and garment manufacture.

Scenario	Electricity	Thermal Energy
1- Business as usual	Grid electricity (100% conventional supply)	Conventional sources (100%): diesel – 13.2%; biomass – 31.2%; furnace oil - 43.2%; LPG – 5.1%; and kerosene 7.2%.
2- Biomass thermal energy	Grid electricity (100% conventional supply)	Biomass – 100%
3- Solar PV electricity	Solar PV – 100%	Conventional sources (100%): diesel – 13.2%; biomass – 31.2%; furnace oil - 43.2%; LPG – 5.1%; and kerosene 7.2%.
4- Solar PV and biomass – partial replacement	50% from conventional supply 50% from Solar PV	50% from conventional sources (same supply mix) 50% from Biomass
5- Solar PV and biomass – Complete replacement	Solar PV – 100%	Biomass – 100%

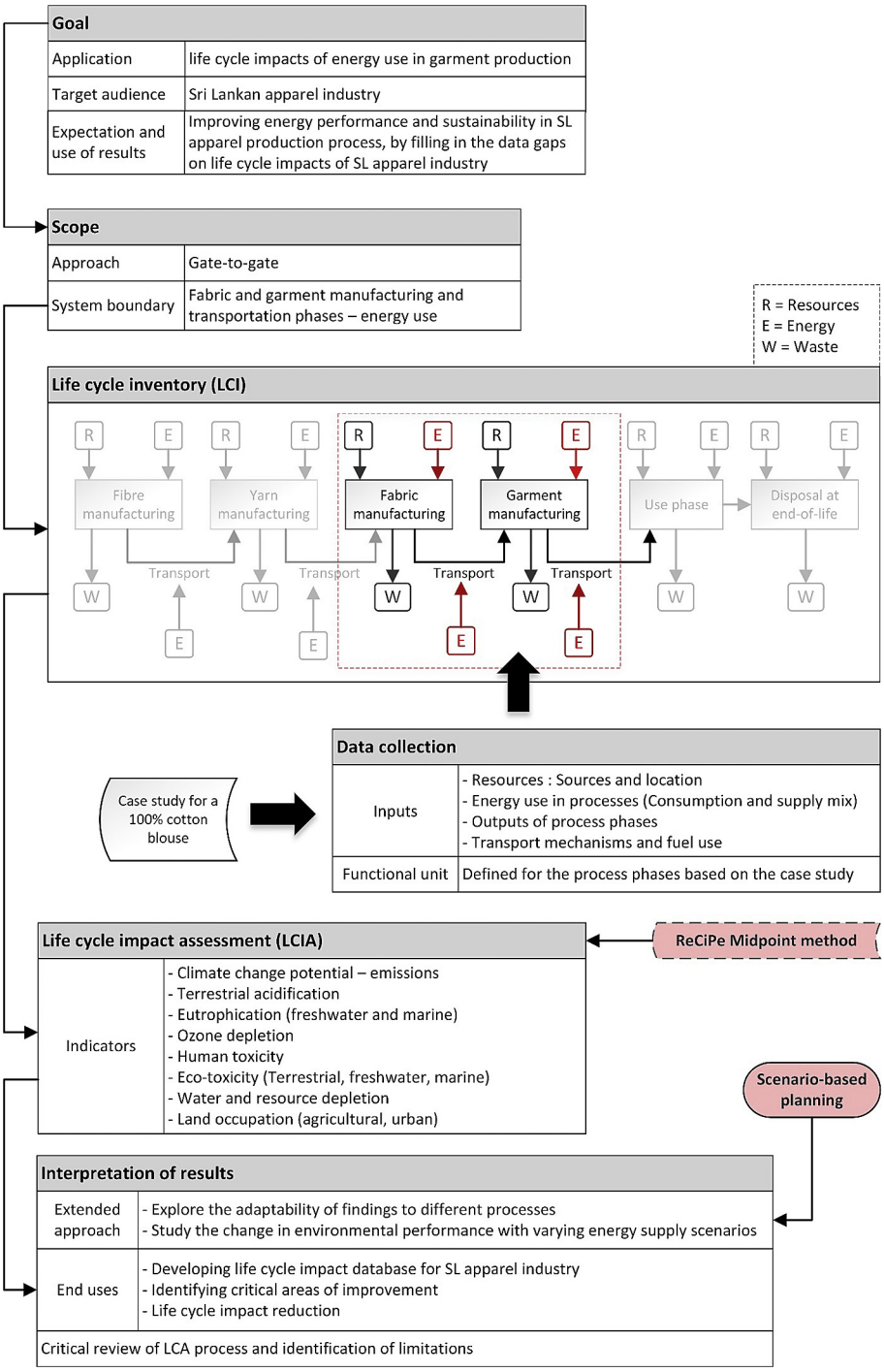

Goal
Application
life cycle impacts of energy use in garment production
Target audience
Sri Lankan apparel industry
Expectation and use of results
Improving energy performance and sustainability in SL apparel production process, by filling in the data gaps on life cycle impacts of SL apparel industry
Scope
Approach
Gate-to-gate
System boundary
Fabric and garment manufacturing and transportation phases – energy use
R = Resources
E = Energy
W = Waste
Life cycle inventory (LCI)
Fibre manufacturing
Yarn manufacturing
Fabric manufacturing
Garment manufacturing
Use phase
Disposal at end-of-life
Transport
Case study for a 100% cotton blouse
Data collection
Inputs
- Resources : Sources and location
- Energy use in processes (Consumption and supply mix)
- Outputs of process phases
- Transport mechanisms and fuel use
Functional unit
Defined for the process phases based on the case study
Life cycle impact assessment (LCIA)
ReCiPe Midpoint method
Indicators
- Climate change potential – emissions
- Terrestrial acidification
- Eutrophication (freshwater and marine)
- Ozone depletion
- Human toxicity
- Eco-toxicity (Terrestrial, freshwater, marine)
- Water and resource depletion
- Land occupation (agricultural, urban)
Scenario-based planning
Interpretation of results
Extended approach
- Explore the adaptability of findings to different processes
- Study the change in environmental performance with varying energy supply scenarios
End uses
- Developing life cycle impact database for SL apparel industry
- Identifying critical areas of improvement
- Life cycle impact reduction
Critical review of LCA process and identification of limitations

Fig. 2. LCA methodology for apparel industry.

3.1. Comparison of life cycle impacts in different process phases

Fig. 3 depicts a graphical comparison of the impact values per garment, for the 12 key impact indicators relevant in assessing the environmental impact of the industry. The normalised scores under each impact category was used in the representation.

It can be seen that the garment manufacture phase has the highest contribution to the environmental impacts of a garment during the selected process phases in the apparel life cycle. In contrast to garment and fabric manufacture phases, the impact due to transportation is negligible. This has been further illustrated in Fig. 4, where the percentage contribution of each process phase can be seen. It can be seen that for most impact categories, over 50% of the contribution comes from the garment manufacture phase.

3.2. Comparison of life cycle impacts under alternative energy scenarios

Table 8 lists the aggregate life cycle impacts of energy use in fabric and garment manufacture under different energy supply scenarios.

The information is graphically presented in Fig. 5. The

Table 6
Life cycle impacts of garment production.

Impact indicators	Unit	Grid electricity	Other energy	Total impacts in garment manufacture	Total impacts in fabric manufacture
		Per Clock hr	Per Clock hr	Per garment	Per garment
Climate change	kg CO2 eq	1.29E+00	6.22E-01	9.49E-01	7.27E-01
Ozone depletion	kg CFC-11 eq	9.40E-08	8.60E-08	8.95E-08	5.30E-08
Terrestrial acidification	kg SO2 eq	8.67E-03	3.21E-03	5.90E-03	4.89E-03
Freshwater eutrophication	kg P eq	3.08E-04	2.65E-05	1.66E-04	1.74E-04
Marine eutrophication	kg N eq	3.34E-04	2.32E-04	2.81E-04	1.88E-04
Human toxicity	kg 1,4-DB eq	2.48E-01	1.37E-01	1.91E-01	1.40E-01
Photochemical oxidant formation	kg NMVOC	4.71E-03	2.06E-03	3.37E-03	2.66E-03
Particulate matter formation	kg PM10 eq	2.52E-03	1.07E-03	1.78E-03	1.42E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	7.43E-05	8.38E-05	7.86E-05	4.19E-05
Freshwater ecotoxicity	kg 1,4-DB eq	6.05E-03	2.72E-03	4.36E-03	3.41E-03
Marine ecotoxicity	kg 1,4-DB eq	6.35E-03	3.10E-03	4.69E-03	3.58E-03
Ionising radiation	kBq U235 eq	4.12E-02	3.59E-02	3.83E-02	2.32E-02
Agricultural land occupation	m^2a	1.14E-02	4.91E-01	2.50E-01	6.51E-03
Urban land occupation	m^2a	7.66E-03	3.21E-03	5.40E-03	4.32E-03
Natural land transformation	m^2	2.11E-04	1.69E-04	1.89E-04	1.19E-04
Water depletion	m^3	1.17E-02	3.58E-04	6.02E-03	6.63E-03
Metal depletion	kg Fe eq	7.60E-03	5.29E-03	6.41E-03	4.29E-03
Fossil depletion	kg oil eq	3.38E-01	2.06E-01	2.71E-01	1.91E-01

Table 7
Life cycle impacts of transportation.

Impact indicators	Unit	Total impacts - Sea	Total impacts - Road	Total impacts in transportation
		per garment	per garment	per garment
Climate change	kg CO_2 eq	4.27E-02	3.31E-03	4.60E-02
Ozone depletion	kg CFC-11 eq	7.05E-11	6.55E-10	7.25E-10
Terrestrial acidification	kg SO_2 eq	1.33E-03	9.27E-06	1.34E-03
Freshwater eutrophication	kg P eq	1.21E-07	2.44E-07	3.65E-07
Marine eutrophication	kg N eq	4.01E-05	1.12E-06	4.12E-05
Human toxicity	kg 1,4-DB eq	1.40E-04	1.07E-03	1.21E-03
Photochemical oxidant formation	kg NMVOC	1.13E-03	1.07E-05	1.14E-03
Particulate matter formation	kg PM10 eq	4.01E-04	5.83E-06	4.06E-04
Terrestrial ecotoxicity	kg 1,4-DB eq	1.33E-07	1.86E-06	1.99E-06
Freshwater ecotoxicity	kg 1,4-DB eq	8.93E-07	3.92E-05	4.01E-05
Marine ecotoxicity	kg 1,4-DB eq	1.07E-05	4.67E-05	5.74E-05
Ionising radiation	kBq U235 eq	8.59E-05	3.01E-04	3.87E-04
Agricultural land occupation	m^2a	0.00E+00	6.07E-05	6.07E-05
Urban land occupation	m^2a	0.00E+00	3.68E-04	3.68E-04
Natural land transformation	m^2	0.00E+00	1.33E-06	1.33E-06
Water depletion	m^3	3.20E-06	3.09E-06	6.28E-06
Metal depletion	kg Fe eq	8.88E-06	1.20E-04	1.29E-04
Fossil depletion	kg oil eq	1.20E-02	1.29E-03	1.33E-02

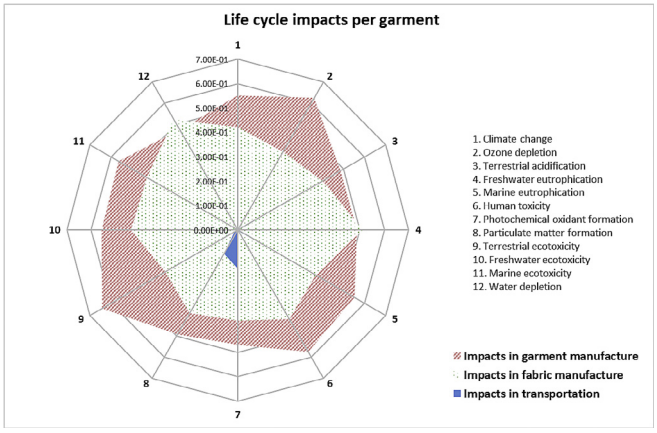


Fig. 3. Comparison of life cycle impacts in key process phases.

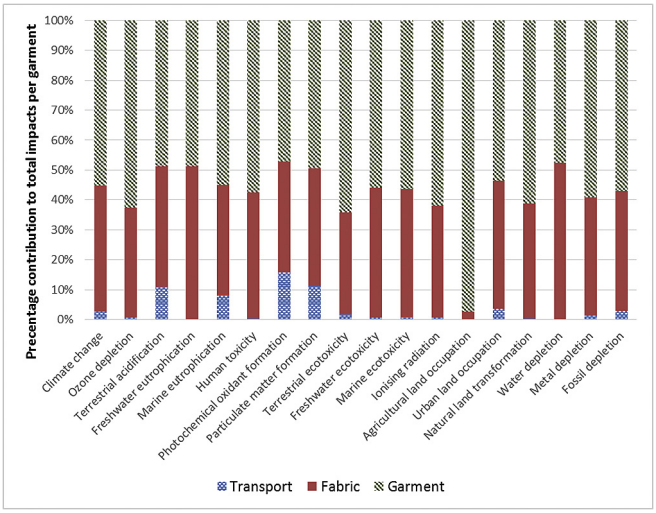


Fig. 4. Relative contribution to total impacts per garment from each process phase.

Table 8
Life cycle impacts under different energy supply scenarios.

Impact indicators	Unit	Impacts per garment				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Climate change (kg CO_2eq)	kg CO2 eq	1.68E+00	1.45E+00	3.03E-01	8.78E-01	8.01E-02
Ozone depletion (kg CFC-11eq)	kg CFC-11 eq	1.42E-07	1.04E-07	5.07E-08	7.71E-08	1.18E-08
Terrestrial acidification (kg SO2eq)	kg SO2 eq	1.08E-02	9.93E-03	1.75E-03	5.84E-03	8.85E-04
Freshwater eutrophication (kg Peq)	kg P eq	3.40E-04	3.55E-04	3.57E-05	1.95E-04	5.05E-05
Marine eutrophication (kg Neq)	kg N eq	4.70E-04	6.22E-04	2.03E-04	4.13E-04	3.56E-04
Human toxicity (kg 1,4-DB eq)	kg 1,4-DB eq	3.31E-01	3.27E-01	8.24E-02	2.04E-01	7.81E-02
Photochemical oxidant formation (kg NMVOC)	kg NMVOC	6.03E-03	6.12E-03	1.07E-03	3.60E-03	1.17E-03
Particulate matter formation (kg PM10eq)	kg PM10 eq	3.20E-03	3.21E-03	5.98E-04	1.91E-03	6.12E-04
Terrestrial ecotoxicity (kg 1,4-DBeq)	kg 1,4-DB eq	1.21E-04	1.07E-04	1.11E-04	1.09E-04	9.72E-05
Freshwater ecotoxicity (kg 1,4-DBeq)	kg 1,4-DB eq	7.77E-03	9.07E-03	4.57E-03	6.82E-03	5.87E-03
Marine ecotoxicity (kg 1,4-DBeq)	kg 1,4-DB eq	8.27E-03	9.18E-03	4.53E-03	6.85E-03	5.43E-03
Ionising radiation (kBq U235eq)	kBq U235 eq	6.15E-02	4.96E-02	2.40E-02	3.68E-02	1.20E-02
Agricultural land occupation (m^2a)	m^2a	2.56E-01	7.91E-01	2.46E-01	5.19E-01	7.82E-01
Urban land occupation (m^2a)	m^2a	9.72E-03	1.21E-02	1.54E-02	1.37E-02	1.78E-02
Natural land transformation (m^2)	m^2	3.08E-04	2.35E-04	9.01E-05	1.62E-04	1.63E-05
Water depletion (m^3)	m^3	1.26E-02	1.21E-02	9.59E-04	6.55E-03	4.61E-04
Metal depletion (kg Fe eq)	kg Fe eq	1.07E-02	1.18E-02	1.31E-02	1.24E-02	1.42E-02
Fossil depletion (kg oil eq)	kg oil eq	4.62E-01	3.84E-01	9.88E-02	2.41E-01	2.09E-02

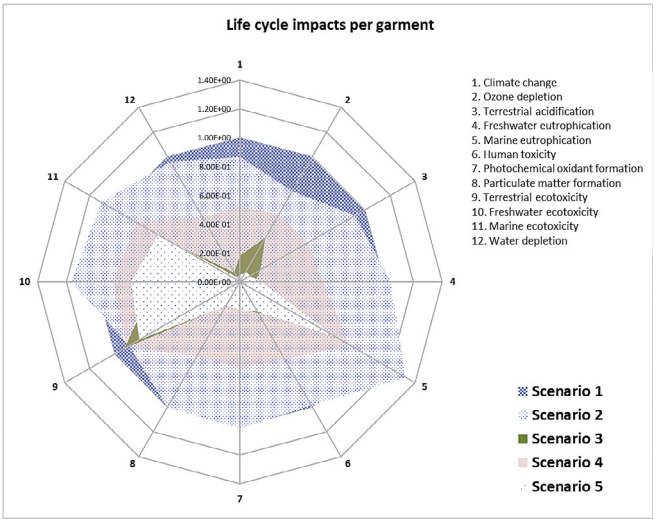


Fig. 5. Comparison of life cycle impacts under different energy supply scenarios.

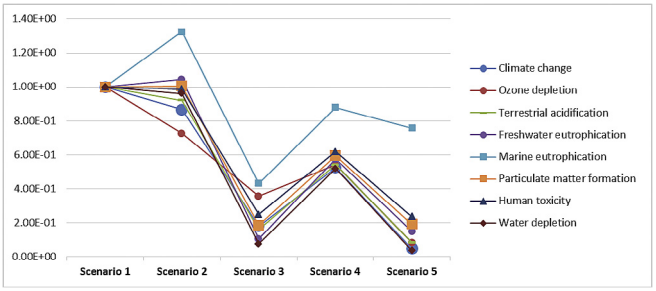


Fig. 6. Variation of impact values with energy supply mix.

normalised scores were used in the representation to compare the scenarios.

It can be noted that the impacts reduce in general with the introduction of renewable energy sources into the supply mix. Replacement of grid electricity with solar PV has the greatest effect on environmental impact reduction.

Fig. 6 depicts the variation of normalised impact values by scenario. The impacts reduce greatly in comparison to the base case under Scenario 3, which is 100% supply of electricity with solar PV. While biomass substation for thermal energy needs appears to reduce some indicator values, the effect is not as high as that of solar PV substitution. In general, the impacts are lowest in Scenario 5, where all thermal and electricity needs are supplied through alternative sources.

4. Discussion and recommendations

In this study, the life cycle impacts of energy use in Sri Lankan apparel industry were investigated through a gate-to-gate approach. The life cycle impact values were assessed on a per garment basis, to identify the environmental costs associated with a single unit of production. The case study was extended to investigate the potential scenario of manufacturing the fabric for the garment within Sri Lanka. A methodology was defined for life cycle impact assessment in the Sri Lankan apparel industry. Further investigation was conducted on alternative energy supply scenarios for the manufacturing process phases. In addition to assisting in developing a life cycle impact database for the SL apparel industry, the findings can be used in identifying the most pivotal areas of improvement in mitigating the life cycle impacts of apparel production and in proposing the most appropriate sustainability measures.

When the different process phases undertaken in apparel manufacturing and distribution were separately assessed for their life cycle environmental impacts, it was identified that the garment manufacture phase has the highest life cycle impacts of energy use. This result can be attributed to the fact that garment manufacture carries the highest specific energy use per garment among the process phases considered in the life cycle of a garment. During this phase, several sub-processes such as washing, cutting, sewing, and finishing take place, requiring electrical and thermal energy. This is an area of concern which needs to be focused on by the garment industry. In order to find out the most critical activities during garment production, it is necessary to separately identify the specific energy consumption of each activity. The environmental impacts due to transportation per garment are almost negligible in comparison with the impacts of manufacturing related activities. For example, as depicted in Fig. 4, transportation accounts for only 2.67% of the incremental climate change potential per garment, measured in kilogrammes of CO_2 emitted, while garment

production accounts for 55%.The life cycle impacts are given on a per garment basis in this study. While on overall the life cycle impacts of shipping and road transport are considerable, they become negligible compared to the other process phases when averaged per garment. While a ship travelling over 20,000 km to USA has a significant environmental impact due to fuel use, the same ship carries thousands of garments and other goods, thus limiting the effect of transportation on each individual garment's environmental footprint. However, when taken as a whole, the life cycle environmental impacts of goods transport by freight and road can be quite considerable. At present, fabric manufacturing is not generally undertaken in SL apparel production facilities due to the lack of infrastructure, and instead fabrics are sourced from other parts of South Asia such as India. In the South Asian apparel sector fossil fuel based energy sources dominate the energy supply. In India, coal, gas, and petroleum account for over 54% of the energy supply for the textile industry, and the remaining part is supplied with electricity (Ray and Reddy, 2008). However, 67% of the Indian grid mix is also supplied with thermal energy sources (i.e. coal, gas, oil) (Ministry of Power - Government of India, 2017). There are considerable life cycle impacts associated with the fossil fuel based energy use as demonstrated through the analysis. Therefore, the above approach can be extended to other parts of South Asia which are engaged in the apparel industry, and thereby to quantify and compare the life cycle impacts under various energy supply scenarios.

The manufacturing industry in its different sectors creates a high environmental burden worldwide. Therefore, it is necessary to explore impact mitigation strategies in the production sector. The source of energy and characteristics of the production process have a significant impact on the environmental impacts created by an industry, and thus, information which extends beyond material and direct energy use need to be considered in assessing the said impacts (Cheah et al., 2013). Sustainability assessment of products need**s** to be extended upstream and downstream along the supply chain, in order to identify the most critical areas of concern (Kucukvar et al., 2016). Different strategies can be employed to reduce the environmental impacts of energy use in manufacturing facilities. One pathway to this goal is through industrial energy management, where energy efficiency and demand reduction practices are implemented at the facility and in its processes (The National Association of Manufacturers, 2005). Reducing energy waste to optimise consumption can be done via making changes at the infrastructure level (through active and passive demand reduction technologies), using energy efficient equipment, and by making changes to industrial processes to enhance efficiency. At the same time, alternative energy sources with a lower environmental footprint can be used to supply the energy needs of the industry.

Conventional fossil fuel sources contribute to the major share of Sri Lankan grid electricity mix, with coal and oil based electricity providing around 62% of the electricity generation. This, in part, is responsible for the high level of environmental impacts associated with the manufacturing processes in the Sri Lankan apparel industry, which heavily relies on grid electricity to supply its energy needs. Moreover, around 69% of the thermal energy supply is also provided through fossil fuel sources such as furnace oil, diesel, kerosene and LPG.

Five different energy scenarios were developed and investigated in this study, in order to compare the life cycle environmental impacts of energy use in apparel production. The energy supply scenarios were defined to investigate the potential effects of complete replacement of thermal sources via biomass, complete replacement of grid electricity supply via solar PV, partial replacement of both thermal and electricity sources, and finally the complete replacement of all energy needs through renewable sources. The overall environmental footprint of the energy use in manufacturing processes reduced considerably when conventional energy sources were replaced with solar PV and biomass. The indicator values of climate change, ozone depletion, and terrestrial acidification reduced by 90–95% from the business-as-usual case when fully replaced with the renewable energy sources. While substituting fossil fuel based thermal energy sources with biomass does not carry benefits as high as that of solar PV, it nevertheless has a reducing effect on the environmental footprint in general. The climate change potential can be reduced by 13% from the current situation by substituting the thermal energy sources entirely with biomass. However, solar PV leads to higher emissions reduction margins compared to biomass, as it is a zero emission technology during the operational phase (Thompson and Duggirala, 2009). These results indicate that apparel industry can achieve significant environmental benefits by replacing conventional energy sources with alternatives, particularly low emission sources such as solar energy.

Even though solar PV is considered to a zero emission technology which greatly reduces environmental impacts compared to the conventional fossil-based energy sources, it can still carry some impacts due to the resource extraction, manufacturing, and disposal phases, especially due to the presence of Zinc and Cadmium based materials (Collier et al., 2014). Thus, it can be seen that the life cycle impacts of the electricity supply with 100% solar PV is still above zero. While biomass performs worse than solar PV in terms of direct emissions, it can lead to a lower toxic material release to the environment compared to solar PV. In fact, in a per unit energy basis, biomass performs better than solar PV under the ecotoxicity impact category based on LCA results.

4.1. Benefits to the stakeholders

The findings of the study can be used by the garment industry in analysing their own sustainability performance, and to take measures in improving the said performance. The critical areas which need attention in reducing the life cycle impacts of the industry can be identified through this approach. By breaking down the high impact processes such as garment production into sub-activities, energy efficient and demand reduction measures can be implemented at production facilities. Moreover, the analysis of the environmental effect of using alternative energy sources is of particular use to the SL apparel industry. This information can be used in exploring sustainability measures, and to assess the feasibility of implementing such strategies at apparel production facilities. Producing “green” labelled products will give a competitive advantage to the Sri Lankan apparel producers in the global market, where eco-friendly products are rising in popularity. The study also investigated the effect of undertaking fabric manufacture within Sri Lanka, in terms of the additional environmental impact. With the growth in the apparel industry within the country, upstream integration of the supply chain has gained interest. Therefore, the findings of the study will be useful to the apparel manufacturers in extending their production activities.

The study revealed that investing in alternative energy technologies can mitigate the environmental burden of the apparel sector. The current trend in the Sri Lankan apparel industry in moving towards RE sources should therefore be promoted and incentivised to ensure long-term energy and environmental sustainability for the sector. The information can be used by decision makers and authorities in formulating policies on promoting sustainable production within the country. Carbon taxes and credits have been used as instruments in promoting sustainable energy use in many parts of the world, including Sri Lanka. However, even

though renewable sources are generally assumed to be zero-emission when determining carbon credits, a life cycle assessment approach reveals that they too, in fact, are responsible for a certain amount of emissions when the total life cycle is considered. The quantification of life cycle impacts of energy use and the actual reduction in those impacts with alternative energy replacements will be useful to decision makers in determining how to incentivise and subsidise RE implementation in the production sector. Emissions and other impact reductions can be encouraged by government support towards technological innovation and the provision of regulations for efficient and effective resource use (Collier et al., 2014).

Furthermore, by moving away from fossil based fuel sources to locally available renewable alternatives, Sri Lankan industry sector and economy can reduce the dependence on foreign energy suppliers. The industrial sector accounts for 25.9% of the total energy demand in Sri Lanka. At present, over 47% of the country's primary energy supply is provided through petroleum and coal (Sri Lanka Sustainable Energy Authority, 2014), and this results in the SL economy being heavily dependent on fossil fuel prices in global markets. By investigating strategies to reduce the dependence on fossil fuels, an added advantage of long-term energy security and economic independence can be obtained in addition to environmental benefits.

4.2. Limitations and further work

The results derived in this study were based on a case study in a Sri Lankan apparel production facility. The equipment use, raw materials, and the production process of the garment can vary depending on the specific characteristics of a product. Thus, the generalisability and adaptability of the results may be limited for another product with significant variations. In addition, assumptions have been made where data was unavailable in the life cycle assessment. The main challenge in developing a life cycle assessment framework for the SL apparel industry is the lack of country-specific data, which is a common feature in the developing countries. As LCA is a novel concept for the SL apparel sector, no reported studies are present on the life cycle impacts of garment production. Furthermore, the fabric materials are commonly sourced from other countries such as India and China (Fernando, 2002), and this information needs to be accounted for in the life cycle inventory (LCI) development and impact assessment. In the present study, the impact data for India and Asia in general were assumed to be applicable to the Sri Lankan context due to the unavailability of country-specific databases. However, the defined approach can be used in evaluating the life cycle impacts of apparel production in Sri Lanka, by adapting to the requirements of case studies. In order to identify the critical sub-activities within a given process phases (e.g. garment production), a detailed investigation through an energy audit at the production facility is necessary. Through this, the specific energy consumption of each activity can be identified for a more detailed LCA.

In conducting a comprehensive study on the life cycle impacts of the apparel industry, the investigation presented in this study needs to be extended to cover all of the processes both upstream and downstream of the actual apparel production. Out of these broad spectrum of areas, the present work only focuses on the energy use in the apparel production process, from the fabric manufacturing phase to eventual distribution to the customers. Hence, further work needs to be performed in quantifying the resource use and emissions in all the process phases. To identify the full life cycle impacts of apparel industry, it is necessary to do an assessment considering the upstream and downstream activities in apparel production, extending from cotton production, manufacture of sub-components and other inputs (including buttons and garment stiffeners), to the eventual disposal of the garment at the end of its life after consumer use. Moreover, such a study should also encompass the effects of resource use and waste generation at each phase of the garment's life cycle, in order to determine the full environmental impacts of the product. Furthermore, the evaluation should be extended to analyse the potential end of life scenarios such as waste disposal and recycling, to devise strategies to implement cradle-to-cradle life cycle concepts in the apparel industry.

5. Conclusion

By conducting an environmental impact assessment on the energy use in Sri Lankan apparel sector operations, it was identified that the garment manufacturing phase results in the highest environmental impacts in general, while transportation results on only a small fraction of the impacts in comparison. The production phase of fabrics and wearing apparel results in significant environmental burdens for the country, particularly as it is a thriving industry, which is critical to the Sri Lankan economy. Providing sustainable solutions to mitigate the said environmental burdens is therefore of great importance. By comparing various alternative energy scenarios to supply the thermal and electric energy needs of the apparel sector, it was identified that solar PV based electricity generation can deliver the highest environmental benefits. The use of solar PV and biomass to replace conventional energy sources in apparel production facilities can reduce the impacts under key impact categories by as much as 90–95%. Substitution of conventional fossil fuel based energy sources with locally available renewable energy sources will also deliver economic benefits to the country in the long run, while also ensuring energy security and energy independence.

Taking an energy sustainable approach in planning the growth of this key industrial sector will also provide a competitive advantage to Sri Lanka in the global market, where eco-friendly products are increasing in popularity. Taking a life cycle perspective as outlined in this study in planning and regulating the apparel sector should be a priority for the decision makers, especially in the governmental bodies. The same approach can be extended to other industrial sectors within the country. To study the full costs and benefits of implementing impact mitigation strategies such as replacement with alternative energy sources, a life cycle cost (LCC) assessment needs to be carried out. Through this approach, the economic feasibility of different energy scenarios can be established. The economic impact assessment should be used in combination with the environmental assessment to select the best impact mitigation strategies for apparel manufacturing organisations.

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